ABUAD Journal of Engineering Research and Development (AJERD)
ISSN (online): 2645-2685; ISSN (print): 2756-6811

Volume 8, Issue 3, 311-320

# Investigating the Mechanical Characteristics of Coconut Fibre/Eggshell Powder/Alumina Reinforced Epoxy Hybrid Composites

Fauziyah Adenike SULAYMAN[1], Amina Yawo ALFA[2], Victor Ndaraba HARUNA[1], Ibrahim SULAIMAN[1], Mohammed ABDULLAHI[1]

[1]*Department of Mechanical Engineering, Federal Polytechnic Bida, Niger state*
suleiman.fausiyat@fedpolybida.edu.ng/haruna.victor@fedpolybida.edu.ng/ibrahim.suleiman@fedpolybida.edu.ng/abdullahi.mohammed@fedpolybida.edu.ng

[2]*Department of Chemical Engineering, Federal Polytechnic Bida, Niger state*
*aminaalfa@fedpolybida.edu.ng*

*Corresponding Author: ibrahim.suleiman@fedpolybida.edu.ng, +2348024729888*
*Received: 07/11/2025*
*Revised: 30/11/2025*
*Accepted: 12/12/2025*
*Available online: 14/12/2025*

***Abstract:*** *The development of hybrid polymer composites reinforced with renewable and waste-derived fillers has been prompted by the growing need for high-performance, sustainable materials. The mechanical behaviour of epoxy-based hybrid composites reinforced with alumina, eggshell powder, and coconut fibre is examined in this work. Tensile, impact, hardness, and wear tests were conducted in compliance with applicable ASTM standards after the materials were manufactured utilizing the hand lay-up method with different reinforcing ratios. With maximum values of 79.80 VHN and a specific wear rate of 0.000438 mm³/Nm, respectively, the results demonstrated that the addition of alumina and eggshell greatly increased hardness and wear resistance. Conversely, composites with higher fibre content exhibited better impact resistance due to improved energy absorption mechanisms, while intermediate formulations with 60% epoxy, 20% coir, 10% alumina, and 10% eggshell demonstrated a balanced combination of strength, toughness, and durability. The results show that appropriate fibre and filler loading optimization can provide lightweight, environmentally friendly composites appropriate for roofing and structural applications, supporting waste conversion and sustainable material development.*

***Keywords:*** *Coconut Fibre, Eggshell Powder, Alumina, Epoxy Composite, Mechanical Properties, Sustainable Materials*

## 1. INTRODUCTION

Research into hybrid composites reinforced using renewable and waste-derived resources has increased because to the growing demand for sustainable materials in manufacturing and construction. Improving material performance while lowering environmental effect is a dual problem for the building sector [1, 2]. Conventional materials offer dependable strength and durability, but their manufacturing processes are frequently energy-intensive and unsustainable. In order to strike a balance between performance and sustainability, this has led to a change in the creation of hybrid composites that incorporate waste fillers and natural fibres [3]. Such composites offer not only ecological benefits but also potential enhancements in mechanical strength, stiffness, and toughness.

Among natural fibres, coconut fibre (coir) has attracted considerable attention due to its abundance, renewability, and favourable mechanical characteristics. Extracted from the husk of coconuts, coir is a readily available agricultural by-product [4]. Coir is a significant by-product of the more than 60 million tonnes of coconuts produced worldwide each year [5]. Coconuts are widely grown in Nigeria, especially in coastal regions like Lagos and Badagry, which offer a steady supply of coir appropriate for composite development [6]. Coconut fibre has been effectively used as a reinforcement in polymer matrices like epoxy resin because to its comparatively high tensile strength and durability, enhancing load-bearing capacity, dimensional stability, and energy absorption [4].

In addition, eggshell powder, a by-product of the poultry and food industries, has emerged as an attractive waste-derived filler for polymer composites. With global egg production exceeding 76 million tonnes per year, large volumes of eggshell waste are generated, posing disposal challenges [7, 8]. An estimated 650,000 tonnes of eggshells are produced in Nigeria alone each year [9]. Eggshell powder, which is high in calcium carbonate, can improve composite materials' overall mechanical stability, stiffness, and hardness [10]. Because it turns agricultural waste into a valuable engineering material, its use is consistent with the concepts of the circular economy.

Furthermore, alumina ($Al_2O_3$) has been widely recognized as an effective ceramic filler that improves the hardness, wear resistance, and thermal stability of polymer composites [11]. When incorporated alongside natural fibres and biogenic fillers, alumina can provide additional reinforcement and particle–matrix interaction, contributing to improved stress transfer and mechanical performance. The combination of coconut fibre, eggshell powder, and alumina within an epoxy matrix offers an opportunity to create a hybrid composite with optimized mechanical properties suitable for various structural and industrial applications.

Therefore, the development and mechanical evaluation of epoxy hybrid composites reinforced with coconut fibre, eggshell powder, and alumina are the main goals of this study. The goal of the study is to process and characterise the developed materials, with a focus on how these reinforcements affect the composites' tensile, impact, and hardness characteristics. It is anticipated that the results would support continued efforts to build sustainable composites, value resources, and develop environmentally friendly materials for engineering applications.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The hybrid composite consists of matrix and reinforcement material. Epoxy hybrid is used as matrix material and was obtained from Stevemore Chemical Co., Kaduna State, Nigeria. The alumina was also obtained from the same source. The coconut fibre was sourced from local markets in Ilori, Kwara State. The eggshells were sourced from local egg sellers and later cleaned and milled in Minna, Niger State

### 2.2 Methods

#### 2.2.1 Preparation of eggshell

The preparation of eggshell powder commenced with the thorough cleaning of collected poultry eggshells. Initially, all adhering egg white residues and inner membrane layers were carefully removed by manually peeling the membrane and rinsing the shells under running tap water. To ensure the microbiological safety of the eggshells and prevent the presence of bacteria, fungi, or other biological agents, the cleaned shells were submerged in a 7% sodium hydroxide (NaOH) solution for a period of 30 minutes. Following chemical treatment, the eggshells were rinsed thoroughly multiple times with clean water to remove traces of NaOH and prevent any adverse reactions during composite fabrication. Post-treatment, the decontaminated eggshells were subjected to natural drying under direct sunlight for a duration of 2–3 days as shown in Figure 1. Once dried, the brittle eggshells were manually crushed into irregular flakes by hand, achieving particle sizes in the range of approximately 0.5 mm to 5 mm [12].

Figure 1: Eggshell preparation; cleaning, grinding and storage

Prior to grinding, the mechanical grinding machine (Figure 1) was carefully inspected and cleaned to remove any residual material or potential contaminants from previous use. The hopper, grinding chamber, and collection outlets were brushed and wiped clean with a dry cloth, followed by a brief air blow to dislodge fine particulates. This step was essential to ensure the purity of the eggshell powder and to prevent cross-contamination from previously processed materials. After grinding, the eggshell powder was sieved using a fine mesh (below 75 µm) to ensure particle uniformity and to remove any unground fragments [12].

#### 2.2.2 Preparation of coconut coir

Coconut coir fibres were washed in distilled water, dried, and then processed in a 10% NaOH solution. The fibre was held at 30°C for 30 min in the alkaline solution. The fibres were again washed in fresh water after treatment and then neutralised with a 2% solution of acetic acid. Then the coir fibre was rewashed in distilled water to eliminate the last residues of acid clinging to them and to attain pH level of about 7 (neutral). These were then dried for 48 h at room temperature to achieve treated fibres as suggested by Singh et al. [13].

#### 2.2.3 Preparation of mould

A square mould with internal dimensions of 120 mm × 120 mm was fabricated for the purpose of casting composite specimens. The mould was constructed using galvanized mild steel sheets as shown in Figure 2, due to their excellent formability, moderate strength, and corrosion resistance, which make them suitable for repeated casting operations under ambient or moderately elevated temperatures.

#### 2.2.4 Composite fabrication

The hand layup method was used for the composite fabrication. The process began with the careful preparation of the mould, adhering to ASTM D2566 standards for mould preparation and release agents as suggested by Nawab et al. [14]. The moulds were cleaned thoroughly to remove any debris and treated with SAE-40 engine to prevent the composite from adhering to its surface during curing. The samples were prepared according to Table 1.

Figure 2: Fabricated mould

Table 1: Formulation of the different composite samples

| Composite sample designation | Volume fraction of epoxy (%) | Volume fraction of coir (%) | Volume fraction of alumina (%) | Volume fraction of eggshell (%) |
|---|---|---|---|---|
| 1 | 100 | - | - | - |
| 2 | 60 | 40 | - | - |
| 3 | 60 | 20 | 5 | 15 |
| 4 | 60 | 20 | 10 | 10 |
| 5 | 60 | 20 | 15 | 5 |
| 6 | 60 | - | 40 | - |
| 7 | 60 | - | - | 40 |

The epoxy resin and hardener were then precisely measured and combined in the 10:1 ratio recommended by Singh et al. [13]. The mould surface was then covered with the blended resin. Using brushes, the first layer of reinforcing coconut fibres was carefully inserted into the mould and saturated with resin. This stage ensures that the fibres are completely soaked with the resin and free of air bubbles, which could jeopardize the composite's structure. Alumina, eggshell powder, and coconut fibres were among the subsequent layers of fibres that were placed one after the other. Each layer was crushed using rollers to eliminate any trapped air and guarantee good adhesion between layers. The procedure will go on until the mould is filled.

Once the layup process is complete, the composite was left to cure at room temperature for 24 h. After curing, the composite was carefully removed from the mould as shown in Figure 3. Any excess material trimmed, and the composite surface polished to achieve the desired finish [15].

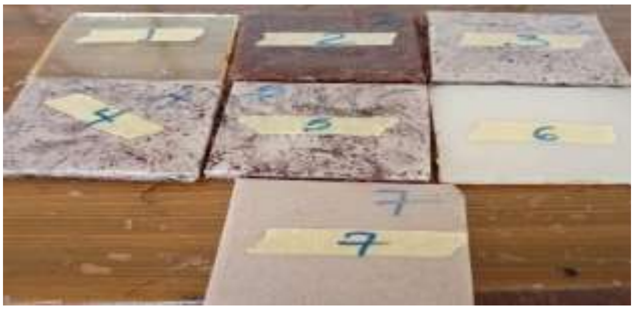


Figure 3: Cured samples of fabricated composites

### 2.2.5 Mechanical tests

**i. Tensile test**

Composite specimens were prepared in accordance with ASTM D3039. The specimens had an average length of 250 mm, a gauge length of 50 mm, a width of 25 mm, and thicknesses corresponding to the laminate dimensions as depicted in Figure 4.

Figure 4: Tensile and impact test samples

The tests were carried out on a WDW-100 kN Universal Testing Machine (UTM) fitted with wedge grips and a 50 mm clip-on extensometer (Figure 5). To calculate the cross-sectional area, the specimen dimensions were measured three times along the gauge section using a vernier calliper. The extensometer was fastened across the gauge length, and each specimen was positioned vertically between the grips [16]. The crosshead was pushed at a velocity of 2 mm/min until fracture occurred after a preload of around 10 N was given to remove slack. The data acquisition system continuously recorded force and elongation.

**ii. Impact test**

A Charpy impact testing apparatus with a protective casing was used to perform impact tests (Figure 5). As seen in Figure 4, composite specimens measuring 65 mm × 12.7 mm × 3.2 mm with a 2.5 mm V-notch at mid-span were prepared in compliance with ASTM D256 [17, 16]. The notch served as a stress concentrator to facilitate fracture. Each specimen was clamped vertically in the machine fixture with the notch facing the striker.

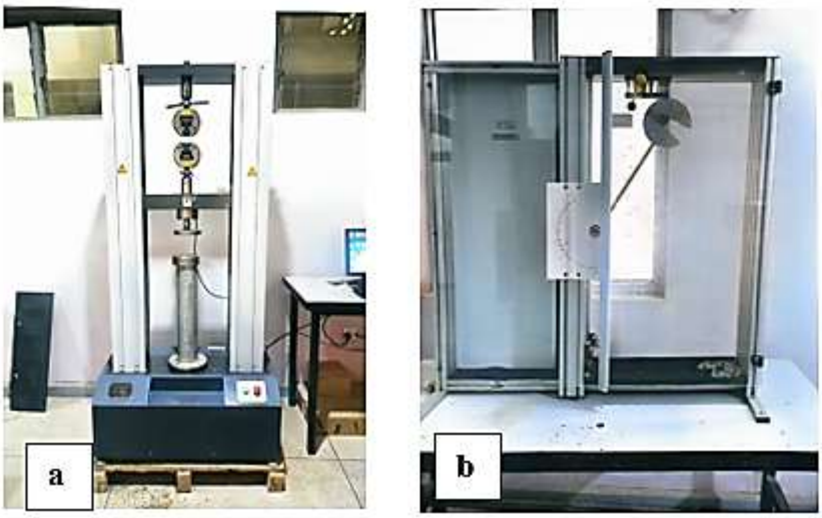


Figure 5: a. Electronic Universal Testing Machine (UTM), b. Impact tester

The pendulum was released from a fixed height to strike the specimen, and the absorbed energy (E) was recorded directly from the dial in joules (J). Tests were repeated for all specimens, and average values were reported as the representative toughness of the composite.

**iii. Hardness test**

A Vickers microhardness tester equipped with a diamond indenter was used to measure the hardness of the developed composites. The test surfaces were polished with a 1 µm diamond suspension to provide a clean surface after the specimens were sliced into tiny rectangular coupons and processed with silicon carbide papers of ever finer grades up to 1200 grit. The polished specimens were cleaned in ethanol, dried, and inspected under an optical microscope prior to testing [18].

A load of 2.94 N was applied for a dwell time of 15 s for each indentation. The Vickers hardness number (VHN) was calculated automatically by the instrument software from the applied load and the mean diagonal length, and the average hardness value for each specimen was reported.

**iv. Wear test**

The wear resistance of the composite specimens was evaluated using a pin-on-disc tribometer in accordance with the ASTM G99 standard. Composite pins of 10 mm diameter and 30 mm length were prepared, with the contact surfaces ground to ensure uniform flatness [19]. Each pin was subjected to a steady 8 N load while being tested against a rotating hardened steel disc. As recommended by Ilori et al. [19], test parameters like the applied load, sliding speed, and sliding distance were set before each run, and the wear track diameter on the disc was modified to correspond with the selected test condition.

The mass of each specimen was recorded before and after testing using an electronic balance with an accuracy of ±0.001 g. The mass loss was used to calculate the specific wear rate (SWR) using Equation 1 [19].

$$\mathrm{SWR} = \frac{\Delta m}{\rho \cdot F \cdot L} \quad (1)$$

where Δm is the mass loss (g), ρ is the density of the composite specimen obtained by the Archimedes method (g/cm³), F is the applied load (N), and $L$is the sliding distance (m). All tests were repeated for each composite formulation, and the average specific wear rate was reported in mm³/N·m units.

## 3. RESULTS AND DISCUSSION

### 3.1 Test Results

The results of the various tests carried out are presented in this section.

#### 3.1.1 Tensile test results

The tensile test results are presented in Figure 6; it contains the yield strength, the tensile strength and the breaking strength values of the fabricated samples. The results reveal a clear variation in mechanical response across the formulations. Samples 6 and 7 with 36.59 and 37.33 MPa exhibit the highest yield strengths respectively, they also exhibit the highest tensile strengths of 49.41 and 47.97 MPa respectively. The presence of high-volume ceramic fillers of 40% eggshell and alumina clearly enhanced stiffness and load-bearing capacity compared to the control sample, with 100% epoxy (sample 1). This indicates that the reinforcement balance in 6 and 7 provided stronger interfacial bonding and better stress transfer, even though fibre is not available in the samples [20, 21].

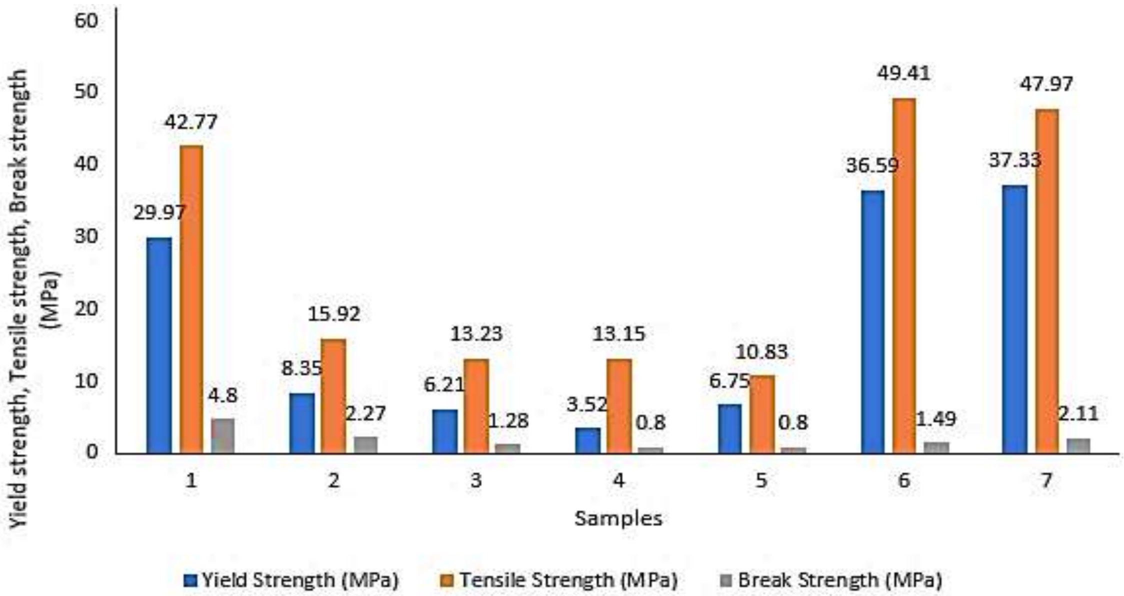


Figure 6: Tensile test results

The low tensile strength in samples 2 to 5 may be linked to the limitations of coir as a reinforcement (in the present study) and the complex interactions with the epoxy matrix and ceramic fillers. In sample 2, high fibre content led to poor fibre–matrix adhesion and fibre pull-out. In samples 3 to 5, the reduced epoxy fraction, combined with particle agglomeration and stress concentration effects, limited stress transfer efficiency. As a result, these composites did not benefit significantly from coir reinforcement in tension, even though they performed better in impact resistance.

Interestingly, sample 1 recorded the highest break strength of 4.8 MPa despite lower tensile strength than 6 and 7, implying a more ductile failure mode. Similar behaviour has been reported in coir/epoxy composites, where fibre pull-out and gradual crack propagation increase energy absorption but lower peak load capacity [22, 23]. The comparatively lower break strengths of 4 and 5 highlight their brittleness which is an important consideration for roofing sheets that must resist impact loading.

### 3.1.2 Impact test results

The impact test results are presented in Figure 7. The impact test results highlight notable differences in energy absorption among the composites. Sample 1 exhibited the highest impact energy of 3.30 J, followed by sample 4 with 2.65 J, while samples 3 and 6 recorded the lowest values of 0.63 J and 0.52 J, respectively. This trend indicates that the formulations achieving the highest tensile strengths (6 and 7 with 40% eggshell and alumina respectively) were also the least capable of resisting impact, suggesting a trade-off between strength and toughness. Studying the composition of sample 4 (coir 20%, alumina 10% and eggshell 10%) shows a balanced mixing ratio for high impact resistance.

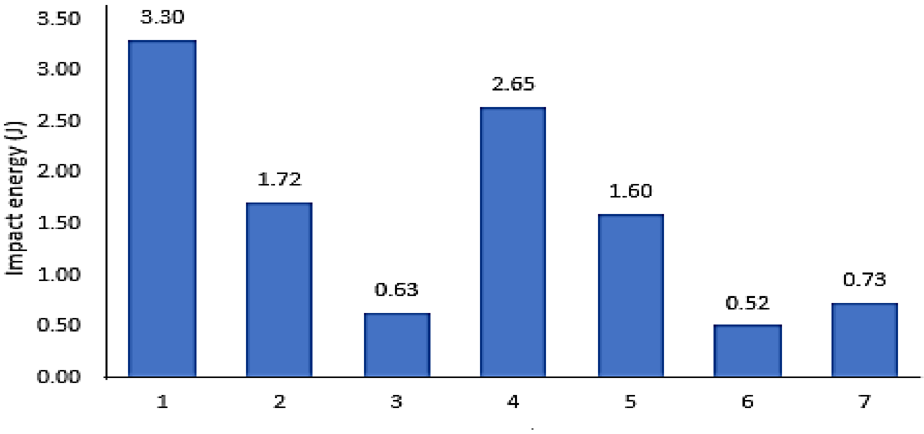


Figure 7: Impact test results

Sample 4, although not the strongest in tensile properties, demonstrated the best impact resistance, implying a more ductile failure mechanism that allows for greater energy absorption before fracture. Similar patterns have been reported in hybrid natural-fibre composites where increased ceramic or mineral filler loading enhances stiffness and tensile strength but reduces toughness due to brittle fracture pathways [22, 24, 25]. Conversely, composites with moderate fibre and filler contents often achieve higher impact energies because mechanisms such as fibre pull-out, crack deflection, and matrix plasticity dissipate more energy during fracture [22]. The relatively high impact energies of samples 1 and 4 may therefore reflect more effective energy-dissipation mechanisms compared with the brittle fracture observed in samples 6 and 7.

The superior impact behaviour of 1 and 4 suggests they may be more reliable for roofing applications where resistance to hail or falling debris is important, even though its tensile strength is lower than that of samples 6 and 7.

### 3.1.3 Hardness test results

The hardness values of the composites increased consistently from sample 1 with 17.17 VHN to sample 7 with 79.80 VHN, reflecting the influence of reinforcement composition. Sample 1, being 100% epoxy, had the lowest hardness due to the ductile and relatively soft nature of the pure polymer matrix. The introduction of coir fibre in sample 2 (60% epoxy, 40% coir) substantially raised hardness to 30.77 VHN, indicating that even organic fibre reinforcement restricted localized deformation to some extent as seen in Figure 8.

Further increases were observed in the hybrid composites of samples 3 to 7, where the inclusion of both alumina and eggshell particles alongside coir progressively improved hardness as seen in Figure 10. These improvements are linked to the stiff, inorganic phases restricting polymer chain mobility and enhancing resistance to indentation.

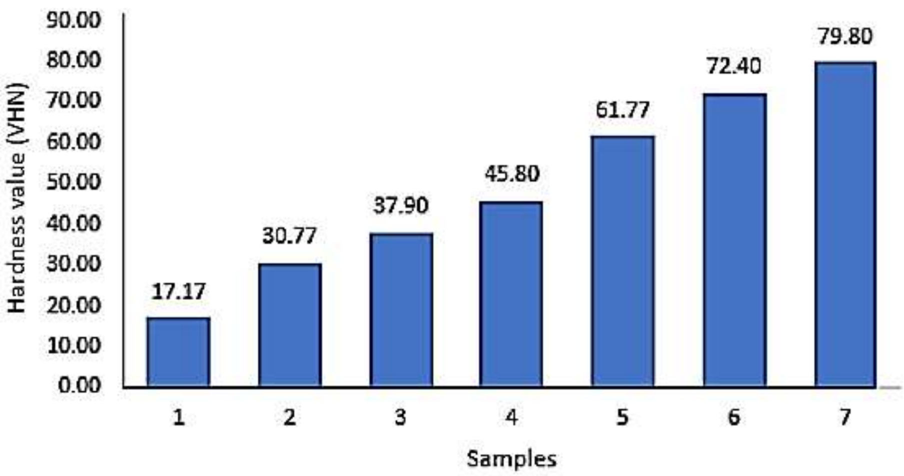


Figure 8: Hardness value results

The highest hardness values were obtained in samples 7 with 60% epoxy, 40% alumina composition and 6 with 60% epoxy, 40% eggshell composition, as 79.80 and 72.40 VHN respectively. Their behaviour confirms the strong stiffening effects of ceramic (alumina) and bio-mineral (eggshell) fillers. Alumina, with its well-documented hardness, and eggshell, rich in $CaCO_3$, both act as effective micro-reinforcements that resist plastic deformation under localized loads [26, 27, 28].

This trend is consistent with literature, where the addition of ceramic and bio-mineral fillers in epoxy systems has been shown to significantly increase hardness [26, 27]. However, the improvement in hardness correlates with lower impact resistance, as seen in samples 7 and 6 (Figure 7), reflecting the common trade-off between rigidity and toughness in hybrid composites.

For roofing applications, higher hardness values are advantageous in terms of wear resistance, surface durability, and protection against scratches or debris. Nevertheless, excessive brittleness in filler-rich systems may limit impact performance under dynamic service conditions. In this regard, intermediate formulations (samples 3 to 5) appear to offer a more balanced compromise between surface hardness and toughness compared to the extremes represented by sample 1 and ceramic-rich composites (7 and 6).

### 3.1.4 Wear test results

The densities of the developed composites were determined using the Archimedes principle. The results which are presented in Table 2. The results were subsequently used to determine the SWR. The densities ranged from 1.485 g/cm³ for sample 1 to 2.858 g/cm³ for sample 7. The variation reflects differences in the type and proportion of reinforcements. samples with higher alumina and eggshell content, such as 6 and 3, recorded significantly higher densities due to the inherent heaviness of ceramic fillers compared to the relatively lightweight coconut fibre and epoxy matrix. In contrast, sample 1, with lower reinforcement loading, exhibited the lowest density, aligning with the need for lightweight composites in roofing applications.

Moderate densities observed in samples 2, 4, 5, and 7 (1.656 to 1.842 g/cm³) suggest a more balanced filler distribution that may offer an optimal compromise between weight and performance. This trend agrees with previous findings that hybrid natural fibre/ceramic composites can be tailored to achieve both light weight and functional strength [29, 30].

The specific wear rate (SWR) of the composites varied noticeably across the samples, ranging from sample 6 having value of 0.000438 mm³/Nm to sample 5 having 0.003398 mm³/Nm as depicted in Table 3. Among the formulations, sample 6 exhibited the lowest wear rate, followed closely by sample 2 with 0.003229 mm³/Nm, suggesting superior tribological performance and resistance to material loss under sliding conditions. In contrast, sample 5 recorded the highest wear rate, indicating relatively poor wear resistance. The improved wear resistance of sample 6 is consistent with its high hardness value of 72.90 VHN, as materials with greater hardness typically resist surface damage and abrasive wear more effectively.

This correlation between hardness and wear resistance has been well established in composite systems, where reinforcement with hard particulates such as alumina or eggshell-derived $CaCO_3$ reduces surface degradation during frictional contact [31]. The relatively high wear rate of sample 5, despite having a moderate hardness of 61.77 VHN, may be attributed to weaker filler–matrix interfacial bonding or suboptimal filler distribution, which could lead to microcracking and particle pull-out under sliding loads.

Interestingly, sample 1 with 0.001686 mm³/Nm and sample 7 with 0.00168 mm³/Nm demonstrated similar wear rates as shown in Figure 9 despite having widely different hardness values (17.17 VHN and 79.80 VHN, respectively). This highlights that wear behaviour is not solely governed by hardness but also influenced by other factors such as filler dispersion, matrix ductility, and synergistic reinforcement effects. Previous studies on hybrid composites have reported similar trends, where composites with very high hardness do not always yield proportionally better wear resistance due to embrittlement and surface micro-fracturing [3, 32].

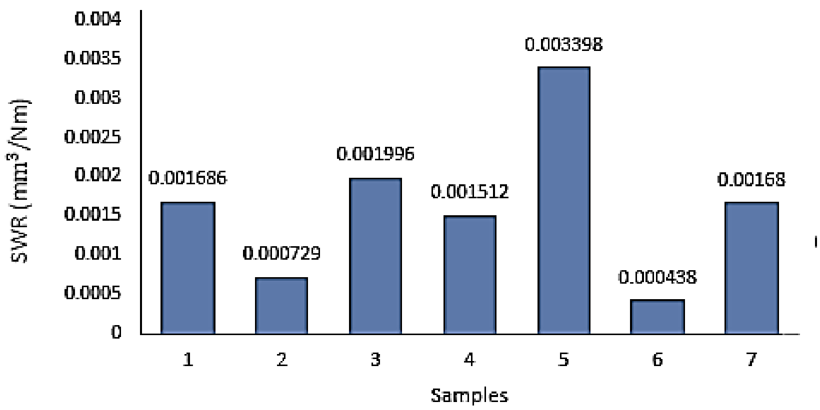


Figure 9: Specific wear rate result

Table 2: Density assesment

| Test 1 using 140 mL container | | | | | Test 2 using 100 mL container | | | | Test 3 using 40 mL container | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sample** | **Mass (g)** | **Volume (ml)** | **Displaced volume (cm3)** | **Density ($g/cm^3$)** | **Mass (g)** | **Volume (ml)** | **Displaced volume ($cm^3$)** | **Density ($g/cm^3$)** | **Mass (g)** | **Volume (ml)** | **Displaced volume ($cm^3$)** | **Density ($g/cm^3$)** | **Average density ($g/cm^3$)** |
| 1 | 4.88 | 143 | 3 | 1.627 | 4.88 | 102.8 | 2.8 | 1.743 | 4.88 | 44.5 | 4.5 | 1.084 | 1.485 |
| 2 | 5.15 | 142.5 | 2.5 | 2.060 | 5.14 | 102.5 | 2.5 | 2.056 | 5.16 | 45 | 5 | 1.032 | 1.716 |
| 3 | 5.8 | 142 | 2 | 2.900 | 5.77 | 101.9 | 1.9 | 3.037 | 5.76 | 46 | 6 | 0.960 | 2.299 |
| 4 | 5.66 | 143 | 3 | 1.887 | 5.66 | 102.9 | 2.9 | 1.952 | 5.65 | 45 | 5 | 1.130 | 1.656 |
| 5 | 6.64 | 143 | 3 | 2.213 | 6.62 | 103 | 3 | 2.207 | 6.63 | 46 | 6 | 1.105 | 1.842 |
| 6 | 4.29 | 141 | 1 | 4.290 | 4.28 | 101.5 | 1.5 | 2.853 | 4.29 | 43 | 3 | 1.430 | 2.858 |
| 7 | 4.33 | 142 | 2 | 2.165 | 4.32 | 102.2 | 2.2 | 1.964 | 4.34 | 44 | 4 | 1.085 | 1.738 |

Table 3: Wear test results

| **Sample** | **Mass before test (g)** | **Mass after test (g)** | **Mass loss (g)** | **Density ($g/cm^3$)** | **Volume loss ($mm^3$)** | **SWR ($mm^3/Nm$)** |
|---|---|---|---|---|---|---|
| 1 | 1.1893 | 1.1887 | 0.0006 | 1.485 | 0.4040 | 0.001686 |
| 2 | 1.4797 | 1.4794 | 0.0003 | 1.716 | 0.1748 | 0.000729 |
| 3 | 2.0268 | 2.0257 | 0.0011 | 2.299 | 0.4785 | 0.001996 |
| 4 | 1.6236 | 1.6231 | 0.0006 | 1.656 | 0.3623 | 0.001512 |
| 5 | 2.2331 | 2.2316 | 0.0015 | 1.842 | 0.8143 | 0.003398 |
| 6 | 1.6578 | 1.6575 | 0.0003 | 2.858 | 0.1050 | 0.000438 |
| 7 | 1.6581 | 1.6573 | 0.0007 | 1.738 | 0.4028 | 0.001680 |

Overall, the wear results suggest that the optimal formulation for tribological applications is sample 6, which combines high hardness with excellent wear resistance. However, in practical applications such as roofing, moderate wear resistance like in sample 2 may be sufficient if coupled with superior impact resistance, thereby ensuring a more balanced performance profile.

## 4. CONCLUSION

This study successfully developed and evaluated coconut fibre, eggshell powder, and alumina reinforced epoxy hybrid composites using the hand lay-up technique. The results demonstrated that reinforcement composition strongly influenced the mechanical behaviour of the composites. Composites containing higher proportions of ceramic fillers, particularly alumina and eggshell, exhibited superior hardness and wear resistance, while those with moderate fibre and filler content showed better impact strength and balanced mechanical performance. The formulation containing 60% epoxy, 20% coir, 10% alumina, and 10% eggshell provided an optimal combination of tensile strength, toughness, and durability, making it a promising candidate for structural and roofing applications.

The study confirms that agricultural and industrial wastes such as coconut fibre and eggshells can be effectively utilized to enhance the mechanical and tribological properties of polymer composites. This not only reduces environmental waste but also promotes sustainable material development for engineering applications. Future work should focus on optimizing fibre treatment, filler dispersion, and long-term durability under environmental loading to further enhance the performance of these eco-friendly composites.

## ACKNOWLEDGMENT

The authors especially are extremely grateful to Tertiary Education Trust Fund (TETFUND), Nigeria. This work has been possible with the financial support of Tertiary Education Trust Fund (TETFUND) under the Institution-Based Research (IBR) Intervention (TETF/DR&D/CE/POLY/BIDA/IBR/2024/VOL. 11).

## REFERENCES

[1] Vagtholm, R., Matteo, A., Vand, B., & Tupenaite, L. (2023). Evolution and current state of building materials, construction methods, and building regulations in the U.K.: Implications for sustainable building practices. *Buildings,* 13(6), 1–21.

[2] Bichof, P., Mata-Falcon, J., & Kaufmann, W. (2022). Fostering innovative and sustainable mass-market construction using digital fabrication with concrete. *Cement and Concrete Research,* 161(22), 1–23.

[3] Chen, F., Sun, L., Luo, H., Yu, P., & Lin, J. (2023). Influence of filler types on wear and surface hardness of composite resin restorations. *Journal of Applied Biomaterials & Functional Materials,* 21(1), 1–8.

[4] Ahmad, J., Majdi, A., Al-Fakih, A., Deifalla, A. F., Althoey, F., El Ouni, M. H., & El-Shorbagy, M. A. (2022). Mechanical and durability performance of coconut fiber reinforced concrete: A state-of-the-art review. *Materials,* 15(10), 1–15.

[5] Obeng, G. Y., Amoah, D. Y., Opoku, R., Sekyere, C. K. K., Adjei, E. A., & Mensah, E. (2020). Coconut wastes as bioresource for sustainable energy: Quantifying wastes, calorific values and emissions in Ghana. *Energies,* 19(9), 1–13.

[6] Uwubanmwen, I. O., Nwawe, C. N., Okere, R. A., Dada, M., & Eseigbe, E. (2011). Harnessing the potentials of the coconut palm in the Nigerian economy. *World Journal of Agricultural Sciences,* 7(6), 684–691.

[7] Pesmen, G. (2023). Possibility of using eggshell in industry. *International Journal of Computational and Experimental Science and Engineering,* 9(4), 331–339.

[8] Das, G., & Biswas, S. (2016). Effect of fiber parameters on physical, mechanical and water absorption behaviour of coir fiber–epoxy composites. *Journal of Reinforced Plastics and Composites,* 35(8), 628–637.

[9] Heise, H., Crisan, A., & Theuvsen, L. (2015). The poultry market in Nigeria: Market structures and potential for investment in the market. *International Food and Agribusiness Management Association,* 18(15), 197–222.

[10] Ndife, J., Onyeiwu, S. C., Kinta, M., & Ibrahim, A. (2022). Development and quality assessment of functional cookies from wheat (*Triticum aestivum*) and chicken eggshell composite flours. *Nigerian Agricultural Journal,* 53(1), 166–171.

[11] Arockiasamy, F. S., Tamil, S. M., Mani, S. K., Satish, S. G., Gokulkumar, I., Iyyadurai, J., & Mani, M. (2024). Fire retardant potential of natural fiber reinforced polymer composites: A review. *Polymer-Plastics Technology and Materials,* 63(4), 1–27.

[12] Sivakumar, A. A., Sankarapandian, S., Avudaiappan, S., & Flores, E. I. S. (2022). Mechanical behaviour and impact of various fibres embedded with eggshell powder epoxy resin biocomposite, *Materials,* 15(24), 1-20.

[13] Singh, Y., Singh, J., Sharma, S., & Lam, T., Nguyen, D. (2020). Fabrication and characterization of coir/carbon-fiber reinforced epoxy-based hybrid composite for helmet shells and sports-good applications: Influence of fiber surface modifications on the mechanical, thermal and morphological properties. *Journal of Materials Research and Technology,* 9(6), 15593–15603.

[14] Nawab, N., Shahid, S., Boyard, N., & Jaquemin, F. (2013). Chemical shrinkage characterization techniques for thermoset resins and associated composites. *Journal of Materials Science,* 48(16), 1–23.

[15] Rządkowski, W., Klik, P., Tracz, J., & Kowalik, M. (2022). Case study of composite chassis manufacturing process using low temperature molds tempered with gradual heat annealing process. *Advances in Science and Technology – Research Journal*, 16(3), 12–21.
[16] Ambali, I. O., Shuaib-Babata, Y. L., Alasi, T. O., Aremu, I. N., Elakhame, Z. U., & Abdulraman, S. O. (2019). Suitability of cow horn as filler in an epoxy composite. *Journal of Applied Science and Environmental Management,* 23(3), 475–482.
[17] Souza, A. T., Neuba, L. D. M., Junio, R. F. P., Carvalho, M. T., Candido, V. S., Figueiredo, A. B.-H. D. S., Monteiro, S. N., Nascimento, L. F. C., & da Silva, A. C. R. (2022). Ballistic properties and Izod impact resistance of novel epoxy composites reinforced with caranan fiber (*Mauritiella armata*). *Polymers,* 14(16), 1–15.
[18] Adediran, A. A., Akinwade, A. A., Balogun, O. A., Olasoju, O. S., & Adesina, O. S. (2021). Experimental evaluation of bamboo fiber/particulate coconut shell hybrid PVC composite. *Scientific Reports,* 21(11), 1–14.
[19] Ilori, O. O., Ojetoye, A. A., Adeleke, K. M., Olorunda, M. O., & Julius, M. O. (2025). Wear behaviour and microstructural characterization of reinforced bio-composite. *OAUSTECH Journal of Engineering and Intelligent Technology,* 1(1), 138–146.
[20] Olarewaju, O., Oladele, I. O., & Adelani, S. O. (2025). A comprehensive review on plant and animal fiber reinforced composites: Experimental and theoretical approaches to interfacial strength optimization and potential applications. *Hybrid Advances,* 10(2025), 1–25.
[21] Ru, S., Zhao, C., Yang, S., & Liang, D. (2022). Effect of coir fiber surface treatment on interfacial properties of reinforced epoxy resin composites. *Polymers,* 14(17), 1–20.
[22] Puttaswamygowda, P. H., Sharma, S., Ullal, A. K., & Shettar, M. (2024). Synergistic enhancement of the mechanical properties of epoxy-based coir fiber composites through alkaline treatment and nanoclay reinforcement. *Journal of Composites Science,* 8(2), 66–72.
[23] Das, S., Mohanty, P. K., & Mallik, R. K. (2022). Agricultural and pharmaceutical applications of eggshells: A comprehensive review of eggshell waste value-added products. *Journal of Pharmaceutical Negative Results,* 13(8), 3979–3984.
[24] Sani, A., Inuwa, I. M., Mustapha, H. M., Yunana, E. U., & Abubakar, M. (2025). Tensile, flexural, impact, hardness and structural characterization of coir fiber/maize husk hybrid composites for electrical fittings. *Science World Journal*, 20(1), 341–355.
[25] Madueke, C. I., Mbah, O. M., & Umunakew, R. (2023). A review on the limitations of natural fibres and natural fibre composites with emphasis on tensile strength using coir as a case study. *Polymer Bulletin,* 80(4), 3489–3506.
[26] Avelino, F. P., Soares, R. A., Pena-Garcia, R. R., & Lobo, A. O. (2023). The effect of the addition of eggshell residues in mass formulation for ceramic coating. *Minerals,* 13(9), 11–23.
[27] Smirnov, A. D., Kholodkova, A. A., Rybalchenko, V. V., & Tarasovskii, V. P. (2023). Porous alumina-bentonite ceramics: Effects of fillers and molding technique. *Ceramics,* 6(1), 132–145.
[28] Miri, Z., Haugen, H. J., Loca, D., Rossi, F., Perale, G., Mohanian, A., & Ma, Q. (2024). Review on the strategies to improve the mechanical strength of highly porous bone bioceramic scaffolds. *Journal of the European Ceramic Society,* 44(1), 23–42.
[29] Suriani, M. J., Ilyas, R. A., Zuhri, M. Y. M., Khalina, A., Sultan, M. T. H., Sapuan, S. M., Ruzaidi, C. M., Wan, F. N., Zulkifli, F., Harussani, M. M., Azman, M. A., Radzi, F. S. M., & Sharma, S. (2021). Critical review of natural fiber reinforced hybrid composites: Processing, properties, applications and cost. *Polymers,* 13(20), 1–14.
[30] Ramful, R. (2024). Mechanical performance and durability attributes of biodegradable natural fibre-reinforced composites—A review. *Journal of Materials Science: Materials in Engineering,* 50(19), 1–20.
[31] Yadav, R., Islam, A., & Dwivedi, V. K. (2024). Wear and microstructure analysis of aluminium-based composite using eggshell and rice husk ash as reinforcement. *World Journal of Engineering,* 21(1), 186–193.
[32] Zhang, Z., Yang, Q., Yang, F., Zhang, H., Zhang, T., Wang, H., & Ma, Q. (2022). Comparative investigation on wear properties of composite coatings with varying $CeO_2$ contents. *Coatings,* 12(7), 1–10.